

Solar wind test of the de Broglie-Proca's massive photon with Cluster multi-spacecraft data

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We use spacecraft data in the solar wind at 1 AU to provide an estimate of the upper limit of the de Broglie-Proca's massive photon, by looking for deviations from the classical Ampère's law. We take advantage of the Cluster spacecraft which allow the direct computation of $\nabla \times \vec{B}$ from simultaneous four-point measurements of the magnetic field. We estimate the upper bound for the mass of the de Broglie-Proca's photon m_γ to be $2 \cdot 10^{-53}$ kg, in agreement with previous findings based on *ad hoc* models in the solar wind.

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Our understanding of the universe is largely based on electromagnetic observations. As photons are the main messengers, fundamental physics has a concern in testing the foundations of electromagnetism. Non-Maxwellian theories can be grouped into two main classes: non-linear and massive photon theories. The former constitute a branch of classical and quantum field theories, and from their conception by Born and Infeld [1], Heisenberg and Euler [2], non-linear theories have been at the heart of the description of a plethora of phenomena. The latter class assume or predict the photon being massive, whereas for the Standard Model the only massless particles are the photon and the graviton, *i.e.* the bosons of the eldest discovered interactions.

The concept of a massive photon has been vigorously pursued by Louis de Broglie from 1922 [3] throughout his life. He defines the value of the mass to be lower than 10^{-53} kg [4]. A comprehensive work of 1940 [5] contains the modified Maxwell's equations and the related Lagrangian. Instead, the original aim of Alexandru Proca [37], was the description of electrons and positrons. Despite Proca's several assertions on the photons being massless, his Lagrangian [6] and formalism [7] apply to a massive real or complex vector field. Theories and conjectures centered on massive photons have been later proposed by several authors. A non-exhaustive list of gauge invariant formalisms includes that of Podolsky, who discuss higher derivatives of the gauge field [8]; of Stueckelberg, who insures gauge invariance by adding a scalar field [9]; of Chern and Simons [10], whose elec-

trodynamics couples the field and the potential in the Lagrangian through the Levi-Civita's tensor. Recent reviews can be found in [11–14]. The concept of massive photons impacts on many fields of physics and astrophysics, *e.g.*, charge conservation and quantization, magnetic monopoles, superconductors, charged black holes and the cosmic microwave background. The relation between the massive photon and the Higgs' boson has been also addressed [12, 15]. The first experimental limits to photon mass were provided by Schrödinger, who pointed out the finiteness of the range of the modified electromagnetism [16, 17].

How much the theory of relativity would be affected by the massive photon assumption, is not straightforward to assess: partly due to the variety of the theories above, and partly to the removal of our ordinary landmarks and the rising of interwoven implications. Indeed, a phenomenologically oriented survey displaying the testable differences among different theories is missing, and experimentalists have mostly conveyed their efforts in checking the simplest and eldest massive photon model, *i.e.* the photon by de Broglie-Proca, henceforth dBP. The upper limits to the photon mass found in such experiments cannot be generalized to other massive photon theories. The massive electromagnetism dBP equations for the electric \vec{E} and magnetic \vec{B} fields were written first by de Broglie [5]. In SI units, they are

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0} - \mathcal{M}^2 \phi, \quad (1a)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad (1b)$$

$$\nabla \cdot \vec{B} = 0, \quad (1c)$$

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$$\nabla \times \vec{B} = \mu_0 \vec{j} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} - \mathcal{M}^2 \vec{A}, \quad (1d)$$

where μ_0 is the free space permeability, ρ the charge density, \vec{j} the current vector, ϕ and \vec{A} are the scalar and vector potentials, $\mathcal{M} = m_\gamma c / \hbar = 1/\lambda$, \hbar being the reduced Planck's constant, c the speed of light, λ the reduced Compton's wavelength, and m_γ the photon mass. Equations (1a-1d) are Lorentz but not gauge invariant, due to the explicit presence of the potentials. This implies that the gauge must be fixed when performing a measurement. Two laws are modified with respect to the original Maxwell's formulation: the curl of the magnetic field (Ampère, 1826 [18]; Maxwell, 1861 [19]), and the divergence of the electric field (Gauss, discovered in 1835 and published in 1867.) The dates of these 19th century achievements are in striking contrast with the current complex and multi-parameterized cosmology.

Experiments have constrained the photon mass to very low limits. A commonly accepted limit from a laboratory experiment (Coulomb's law) is 2×10^{-50} kg [20]. One prediction of the dB-P theory affirms that lower energy photons travel at lower speed than those at higher energies. This prediction behaves like the dispersion from plasma. In pulsar timing, different arrival times of the incoming photons are routinely measured, but lacking any other independent measurement on the electron density, the differences are solely attributed to plasma dispersion. The dispersion-based limit is $3 \cdot 10^{-49}$ kg [21]. A number of different experiments and analysis have been performed on space environments and obtained lower limits. Davis et al. [22] use Pioneer-10 data of the Jupiter magnetic field to set a limit of $8 \cdot 10^{-52}$ kg. Tighter estimates emerge by the analysis of the interplanetary magnetic field in the solar system, although Adelberger et al. [15] question such limits if the photon were to acquire its mass through the Higgs' mechanism. Ryutov found first $m_\gamma < 10^{-52}$ kg in the solar wind at 1 AU [23], and later $m_\gamma < 1.5 \times 10^{-54}$ kg at 40 AU [24]. The latter is the limit currently accepted by the Particle Data Group (PDG) [25]. Even lower limits have been claimed from modeling the galactic magnetic field and are 10^{-62} kg [15, 26]. It should be noted that the lowest theoretical limit on the measurement of *any* mass is prescribed by the Heisenberg's uncertainty principle $m \geq \hbar / \Delta t c^2$, and gives 2.7×10^{-70} kg, where Δt is the currently supposed age of the Universe ($1,37 \cdot 10^{10}$ years). Incidentally, the same principle implies that measurements of masses in the order of 10^{-54} kg should be performed in time scales of about twenty minutes.

An important warning must be flagged. The examination of the literature on the large-scale "astrophysical limits" inspires a critical attitude and prompt to question whether these limits are nothing more than the outcome of idealized models. This view is confirmed by Goldhaber and Nieto [38]. Estimates from planetary [22, 27] and solar wind [23, 24] magnetic fields are likely to be more

reliable, as they are based on *in situ* measurements and the estimated upper limit of photon mass m_γ is closer to laboratory experiments [20]. But even the estimates from *in situ* measurements are based on several assumptions. For the case of the solar wind, a close scrutiny of the last accepted limits [23, 24] reveals that: (i) the magnetic field is assumed exactly always and everywhere a Parker's spiral; (ii) the accuracy of particle data measurements (from e.g. Pioneer or Voyager) has not been discussed; (iii) there is no error analysis. It is then important to verify the robustness of such solar wind estimates by using a more detailed experimental analysis.

Dealing with such a small mass should induce to extreme caution. A small mass needs a very precise experiment or, alternatively, a very large apparatus, since a small mass is associated to a very large (reduced) Compton wavelength λ . In this letter, we focus on the second possibility through the largest-scale magnetic field accessible to *in situ* spacecraft measurements, *i.e.* the interplanetary magnetic field carried by the solar wind. For this purpose, we use the only currently available multi-point spacecraft to test the dBP modified Ampère's law. Cluster [28] is an European Space Agency mission composed by four identical spacecraft flying in tetrahedral configuration. Cluster has allowed for the first time the direct estimate of three-dimensional quantities from four-point *in situ* measurements of particle and electromagnetic fields [28]. The novelty of this approach is that we can directly estimate $\nabla \times \vec{B}$ from magnetic field measurements; this was not possible with earlier spacecraft measurements. For the steady components of the magnetic field, *i.e.* low frequencies, the displacement current term can be dropped, and we thus refer to the Ampère's law. Its dBP modified version reads

$$\nabla \times \vec{B} = \mu_0 \vec{j} - \mathcal{M}^2 \vec{A}. \quad (2)$$

The only experiment able to properly estimate from Eq. 2 the mass m_γ requires the independent, and within experimental errors, measurement of the difference between the currents $\vec{j}_B = \nabla \times \vec{B} / \mu_0$ and $\vec{j} = \vec{j}_P = ne(\vec{v}_i - \vec{v}_e)$, where n is the number density, e the electron charge, and \vec{v}_i , \vec{v}_e are the velocity of the ions and electrons, respectively. To our knowledge, this measurement has never been performed up to now. The dBP photon mass is given by (SI units)

$$m_\gamma = \frac{\hbar}{c} \sqrt{\frac{\mu_0}{|\vec{A}_H|}} \left| ne(\vec{v}_i - \vec{v}_e) - \frac{\nabla \times \vec{B}}{\mu_0} \right|^{\frac{1}{2}} = k |\vec{j}_P - \vec{j}_B|^{\frac{1}{2}}, \quad (3)$$

where $\hbar = 1.05 \cdot 10^{-34}$ J s, $c = 2.99 \cdot 10^8$ m s⁻¹, $\mu_0 = 1.26 \cdot 10^{-6}$ N A⁻², \vec{A}_H is the vector potential of the interplanetary magnetic field, and $k = \hbar \mu_0^{1/2} c^{-1} |\vec{A}_H|^{-1/2}$.

The event selection has been performed according to the following criteria: (i) a calm solar wind event, *i.e.*

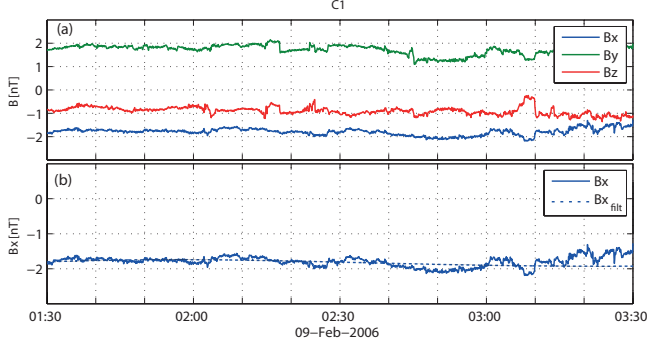


FIG. 1: Panel (a). Three components of the magnetic field for Cluster 1 in the GSE (Geocentric Solar Ecliptic) coordinate system. The magnetic field is measured at 22 samples/s and has been re-sampled at the time resolution of the spacecraft position measurements (1 minute). The GSE coordinate system is defined as having the X direction pointing from the Earth to the Sun, the Z direction orthogonal to the ecliptic plane, and the Y direction completing the right-handed system. Panel (b). The B_x component (solid line), and the same component low-pass filtered below 0.01 Hz (dashed line).

disconnected from the terrestrial bow shock and as far as possible from the terrestrial magnetic field; (ii) the location of the four spacecraft closest to the equatorial plane; (iii) the widest inter-spacecraft separation, namely 10^4 km, for the largest differences in the magnetic field among spacecraft; (iv) the configuration best approaching the tetrahedron; (v) the availability of the ion and electron moments. Figure 1 shows the magnetic field components measured by Cluster for one such event during a time interval of two hours, in the in GSE (Geocentric Solar Ecliptic) coordinate system. It is to be inferred from Fig. 1, that the magnetic field has $B_x < 0$, $B_y > 0$ and $B_x, B_y \gg B_z$, as expected for the Parker's spiral close to the ecliptic plane, where Cluster passes at the selected event. It is emphasized, however, that our analysis does not rely on the Parker's model, since the magnetic field is measured *in situ*. The choice of one event having Parker's spiral orientation is to have conditions as similar as possible to those present in [23, 24]. For this event, $A_H \sim < |\vec{B}_0| > \times L = 2.65 \cdot 10^{-9} \times 1.5 \cdot 10^{11} = 4 \cdot 10^2$ T m, where $< |\vec{B}_0| >$ is the value of the magnetic field measured by Cluster, Fig. 1, and L , distance of Cluster from the Sun, is 1 AU in meters.

In this paper, we estimate $\nabla \times \vec{B}$ by using the curlometer method [29, 30] on the magnetic field from the Cluster flux-gate magnetometer data [31]. This method allows (i) to compute the average $\nabla \times \vec{B}$ over the spacecraft tetrahedron with no assumptions on the field analytical form (only assuming linear gradients); (ii) to assess the error on the average of the current $\nabla \times \vec{B}/\mu_0$

$$\frac{\Delta j_B}{< j_B >} = \frac{\Delta B}{< B >} + \frac{\Delta R}{< R >}, \quad (4)$$

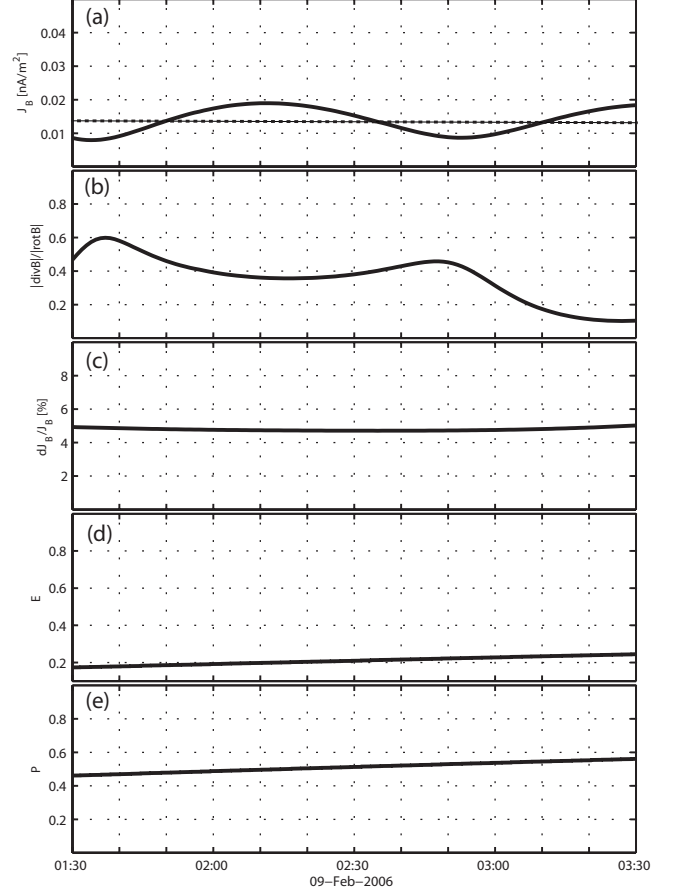


FIG. 2: Panel (a). The current density computed with the curlometer method. The dashed horizontal line corresponds to its average value. Panel (b). Estimate of the deviations from linearity for the curlometer method, where the lower values are associated to higher linearity. Panel (c). Relative error for the current of the current density. Panel (d). Elongation of the tetrahedron $0 < E < 1$. An elongation of zero, corresponds to a perfect tetrahedron. Panel (e). Planarity of the tetrahedron $0 < P < 1$. Planarity equals to zero corresponds to a perfect tetrahedron.

with ΔB being the error on the average of the magnetic field, and ΔR the error on the average of the spacecraft separation R ; (iii) to estimate the deviation from the linearity assumption through the quantity $|\nabla \cdot \vec{B}|/|\nabla \times \vec{B}|$. Figure 2 shows the result of the curlometer for the event of Fig. 1, after having low-pass filtered the magnetic field with $f_{LP} = 0.01$ Hz to remove the magnetohydrodynamic (MHD) waves, as we are interested to the steady components of the magnetic field only.

Our appraisal of $j_B = |\nabla \times \vec{B}|/\mu_0$ is $1.37 \cdot 10^{-11} \pm 5.27 \cdot 10^{-13}$ A m⁻². The relative error $\Delta j_B / < j_B >$ is about 5%, obtained by assuming $\Delta B = 0.1$ nT (accuracy of the magnetometer), $< R > = 10^4$ km (spacecraft separation), $\Delta R = 1\% \times < R > = 100$ km. The accuracy of this esti-

mate is satisfactory, as indicated by the small relative error, and by the reasonable value of $|\nabla \cdot \vec{B}|/|\nabla \times \vec{B}| \sim 50\%$, in agreement with earlier accuracy estimates [30]. The values elongation ~ 0.2 planarity ~ 0.5 of the tetrahedron are within the range for accurate estimates [30].

Conversely, a meaningful assessment of the current density from the ion and electron moments is not possible due to inherent instrument limitations. Ion electrostatic analyzers, such as that on-board Cluster [32], can saturate in the solar wind due to the presence of high fluxes, and thereby resulting often in incorrect ion moments. Further, the computation of the moments from the electron electrostatic analyzers on-board Cluster is affected by photoelectrons and spacecraft charging issues [33]. The assessed value of the current from the particle detectors for this event (as well as for other events) is much larger than those from the curlometer (this is mostly due to the differences in the velocities, while the estimate of particle density is reasonable). These large values are not consistent with the values expected from the difference $|\vec{j}_P - \vec{j}_B|$, based on earlier findings of the upper limit of m_γ , in the range $10^{-54} - 10^{-50}$ kg. Besides, measurements in other regions of space, *e.g.* Earth's magnetosphere, typically show that this difference is small [34]. We have therefore disregarded particle instrument data to avoid unjustified claims on experimental limits, or even more, on the discovery of a massive photon. Nevertheless, we can still put a conservative upper limit on m_γ . We write (for Δ indicating the absolute error)

$$m_\gamma \leq k [j_P + \Delta j_P - (j_B - \Delta j_B)]^{\frac{1}{2}}. \quad (5)$$

We assume that $j_P - j_B$ is very small, and thus

$$m_\gamma \lesssim k [j_B (\epsilon_P + \epsilon_B)]^{\frac{1}{2}}, \quad (6)$$

where $\epsilon_{P,B}$ are the relative errors. We further assume that such errors are comparable. A worst case estimate based on particle data leads to $\epsilon_P \sim 1$, and thereby implying a factor 3 on the upper limit of m_γ . Relying on these two assumptions, the estimate comes from the error of the curlometer

$$m_\gamma \lesssim k(2\epsilon_B j_B)^{\frac{1}{2}} = 2.83 \cdot 10^{-47} (\Delta j_B)^{\frac{1}{2}} \text{ kg}, \quad (7)$$

that is $m_\gamma \lesssim 2 \cdot 10^{-53}$ kg, for $\Delta j_B = 5.27 \cdot 10^{-13} \text{ A m}^{-2}$.

This value is one order of magnitude smaller than the earlier estimate in the solar wind at 1 AU [23], but one order of magnitude larger than the estimation done at 40 AU [24], that is the currently accepted limit by PDG [25]. Our value of m_γ from a detailed experimental analysis is thus in agreement with such estimates coming from *ad hoc* models. On the other hand, our estimate is three orders of magnitude smaller than laboratory limit [20].

Improvements of this estimate could come from a better accuracy of spacecraft separation and, most importantly, of magnetic field measurements, as well as from

more accurate particle measurements. We have considered a conservative error for the spacecraft separation of 1%, corresponding to about 100 km. Nevertheless, typical values from the literature are smaller, *i.e.* 5 – 10 km [30], thereby reducing the contribution of the spacecraft position error to Δj_B by a factor of 10 – 20. However, since the largest contribution to Δj_B comes from the error on the magnetic field measurements, the improvement in the accuracy of separation would not be crucial. A better accuracy of the measurements from the fluxgate magnetometer is more consequential. For our estimate, we have conservatively adopted $\Delta B = 0.1 \text{ nT}$ as typical accuracy for the fluxgate magnetometer on-board Cluster. An accuracy of 0.01 nT would result in an improvement factor of about 3 on the upper limit of m_γ . Such accuracy is already included in the specifications of fluxgate magnetometers, such as those on-board Cluster [31], or Cassini [35] spacecraft. Further advances may be achieved in the future by more accurate magnetometers.

Undoubtedly, the most stringent requirement comes from the particle detectors. For the event studied here, the difference between ion and electron velocities is

$$|\vec{v}_i - \vec{v}_e| = \frac{j_P}{ne} \simeq 6.2 \cdot 10^{11} j_P \text{ m s}^{-1}, \quad (8)$$

where $n \sim 10^7 \text{ m}^{-3}$ (ion density measured for this event) and $e = 1.6 \cdot 10^{-19} \text{ C}$. By assuming the current density to be similar to that given by the curlometer, that is $j_P = j_B = 1.37 \cdot 10^{-11} \text{ A m}^{-2}$, the difference of ion and electron velocities should be less than 10 m s^{-1} . This velocity difference cannot be measured neither by the electrostatic analyzers on-board Cluster, nor by more recent ones. The typical energy resolution $\delta E/E$ of such detectors is several percents [32, 33]. By assuming $\delta E/E \sim 10\%$, and a typical value of particle energy in the solar wind $E \sim 10 \text{ eV}$, the resolution for the velocity is $\delta v_e \sim 95 \text{ km s}^{-1}$ for the electrons, and $\delta v_i \sim 2 \text{ km s}^{-1}$ for the ions. It is straightforward to see that such detectors cannot resolve a velocity difference of 10 m s^{-1} .

Few other considerations are worth mentioning. The Planck and the permeability (or magnetic) constants are depending on the definition of the speed of light which in itself depends on the photon mass. Therefore, there is an underlying epistemological contradiction in the equations above. Given the size of the errors in the currents and in the vector potential, the error contributions from the constants were neglected.

Most non-Maxwellian theories foresee a deviation from the Ampère's law. An analysis of these theories versus Cluster data is planned [39]. These investigations emphasize the importance of a dedicated space measurement.

We have reported a novel test for estimating the upper limit of the dBP massive photon by using Cluster multi-spacecraft measurements in the solar wind. We have found $m_\gamma < 2 \cdot 10^{-53} \text{ kg}$, in agreement with previous solar wind estimates, but our test being based on fewer assumptions than previous results. First, we have

directly assessed $\nabla \times \vec{B}/\mu_0$ from four-point magnetic field measurements; this was not possible before. Second, our test does not assume that the interplanetary magnetic field is a Parker's spiral. Third, is the only measurement performed so far in the solar wind that takes into account in detail the effect of experimental errors. Finally, though the de Broglie's prediction on the upper limit of the photon mass is confirmed [3], the domain between the laboratory findings ($m_\gamma < 10^{-50}$ kg) and the solar wind results ($m_\gamma < 10^{-54}$ kg) is still subjected to assumptions and conjectures, though fewer now, and not to clear-cutting

outcomes from experiments. Our experiment is limited by the resolution of the velocity differences of ions and electrons.

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